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**EVALUATION OF CATALYTIC AND THERMAL  
CRACKING IN A JP-8 FUELED PULSED DETONATION  
ENGINE (POSTPRINT)**

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**Combustion Branch  
Turbine Engine Division**

**SEPTEMBER 2007**

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<b>14. ABSTRACT</b> Pulsed detonation engines (PDEs) depend on rapid ignition and transition from deflagration to detonation. The prospect of converting the PDE from experimental to operational use necessitates a considerable reduction in the time required to ignite and detonate a liquid hydrocarbon fuel in air, such as JP-8. This research effort is focused on PDE operation enhancements using dual detonation tube, concentric-counter-flow heat exchangers to elevate the fuel temperature levels sufficiently to induce thermal cracking. Additionally, a zeolite catalytic coating is applied to the heat-exchanger surfaces to stimulate further cracking of the fuel and reduce coke deposition. To quantify the PDE performance, three parameters are examined: ignition time, deflagration-to-detonation transition (DDT) time, and DDT distance. Once cracked, the JP-8/air mixture results in a shorter ignition time, DDT time, and DDT distance for the majority of equivalence ratios, with a reduction in ignition time of up to 60% at 908 K, as compared to flash vaporized JP-8/air mixtures. Furthermore, both the ignition and detonability limits are expanded by cracking the fuel, with lean limits at an equivalence ratio of 0.75. Coke deposition found in the fuel filter consists of carbon as well as substantial concentrations of silicon and aluminum, due to breakdown of the silica-alumina zeolite structure. Additionally, poisoning of the catalyst is shown to occur after five hours of operation, although no degradation in performance was observed.					
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# Evaluation of Catalytic and Thermal Cracking in a JP-8 Fueled Pulsed Detonation Engine

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Pulsed detonation engines (PDEs) depend on rapid ignition and transition from deflagration to detonation. Converting the PDE from experimental to operational use will necessitate a considerable reduction in the time required to ignite and detonate a liquid hydrocarbon fuel, such as JP-8, in air. This research effort is focused on PDE operation enhancements using dual-detonation-tube, concentric-counter-flow heat exchangers to elevate the fuel temperature levels sufficiently to induce thermal cracking. Additionally, a zeolite catalytic coating is applied to the heat-exchanger surfaces to stimulate further cracking of the fuel and reduce coke deposition. To quantify the PDE performance, three parameters are examined, ignition time, deflagration-to-detonation transition (DDT) time, and DDT distance. As compared with flash-vaporized JP-8/air mixtures, the cracked JP-8/air mixture produces a shorter ignition time, DDT time, and DDT distance for the majority of equivalence ratios, with a reduction in ignition time of up to 60% at 908 K. Furthermore, both the ignition and detonability limits are expanded by cracking the fuel, with lean limits at an equivalence ratio of 0.75. Coke deposition found in the fuel filter consists of carbon as well as substantial concentrations of silicon and aluminum, resulting from deterioration of the silica-alumina zeolite structure. Additionally, the catalyst was coated in coke deposition after 5 hr of operation, although no degradation in performance is observed.

## Nomenclature

$E_{crit}$	=	Critical Initiation Energy
$M_{CJ}$	=	Chapman-Jouguet Mach Number
$P_o$	=	Initial Fuel/Air-Mixture Pressure
$\gamma_o$	=	Initial Fuel/Air-Mixture Ratio of Specific Heats
$\lambda$	=	Cell Size

## I. Introduction

THEORETICALLY, the pulsed-detonation-engine (PDE) cycle can provide nearly constant-volume combustion, with lower entropy gain and higher propulsive efficiency; but practical PDEs are still in the early stages of development.<sup>1-3</sup> Several technological barriers must be overcome before the PDE can be considered a realistic means of providing propulsion to operational aircraft.<sup>4</sup> A large barrier is the efficient ignition and detonation

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initiation of low-vapor-pressure hydrocarbon fuels such as JP-8. While a substantial amount of research has been performed with gaseous fuels such as hydrogen and simple hydrocarbons,<sup>5</sup> only recently have studies on liquid hydrocarbon fuels been conducted.<sup>6</sup> This lack of research has resulted in a large gap between experimental and the operational use of PDEs. Nearly all United States Air Force (USAF) aircraft are operated with liquid hydrocarbon fuels primarily JP-8.<sup>7</sup> Therefore, the ability to utilize those fuels efficiently in the PDE is necessary to transition PDE technology from the research phase to the operational-use phase.

The conversion from gaseous fuels to liquid hydrocarbon fuels has highlighted three key cycle-performance parameters that adversely affect efficient PDE operation: 1) time from spark deposition to the creation of a deflagration wave within the fuel/air mixture (ignition time), 2) the time required to transition the deflagration wave into a detonation wave (DDT time), and 3) the length of detonation tube required for the mixture to transition to a detonation (DDT distance). Both the ignition time and the DDT time are nearly an order of magnitude longer for complex liquid hydrocarbon fuels than for hydrogen. For example, the ignition time for a hydrogen/air mixture is on the order of 1 ms, whereas that for a JP-8/air mixture is ~7 ms.

This research marks the first evaluation of a PDE fueled with thermally and catalytically cracked JP-8 fuel. Previous research<sup>8,9</sup> demonstrated the benefits of preheating JP-8 to flash vaporization and supercritical temperatures. Tucker et al.<sup>8</sup> demonstrated that flash vaporization of JP-8 reduces both ignition time and DDT time, as well as increases the ignition and detonation limits. Helfrich et al.<sup>9</sup> found that heating JP-8 to supercritical temperatures caused a decrease in DDT time and DDT distance and improved the consistency of detonations. The focus of the present research was to use a dual-detonation-tube, concentric-counter-flow heat-exchanger system to elevate the fuel temperatures sufficiently to crack the fuel thermally with the assistance of a zeolite catalytic coating.

## II. Background and Theory

Previous experimental research<sup>5</sup> has shown that a typical, stoichiometric, low-vapor-pressure liquid-hydrocarbon/air mixture requires on the order of  $10^5$  J of energy for direct initiation of detonation (critical initiation energy), which is six orders of magnitude greater than that available from a typical spark plug (~100 mJ). Thus, a mixture with low critical initiation energy is more susceptible to DDT. Knystautas et al.<sup>10</sup> developed a correlation between the detonation cell size ( $\lambda$ ) and the critical initiation energy of a mixture, shown in Eq (1):

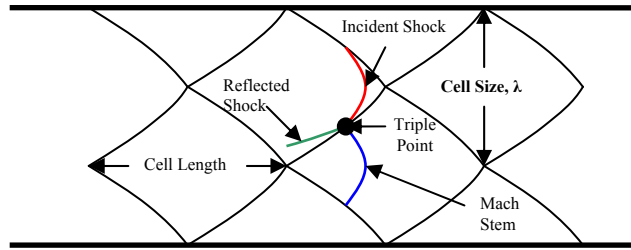
$$E_{crit} = (2197/16)\pi\gamma_o P_o M_{CJ}^2 I \lambda^3 \quad (1)$$

where  $E_{crit}$  is the critical initiation energy of a fuel/air mixture,  $\gamma_o$  is the initial ratio of specific heats,  $P_o$  is the initial mixture pressure,  $M_{CJ}$  is the Chapman-Jouget Mach Number of the mixture, and  $I$  is a dimensionless constant. Additionally, Schauer et al.<sup>11</sup> developed a correlation for the detonation cell size and the critical initiation energy of a mixture based on data gathered by Kaneshige and Shepherd,<sup>5</sup> Eq. (2):

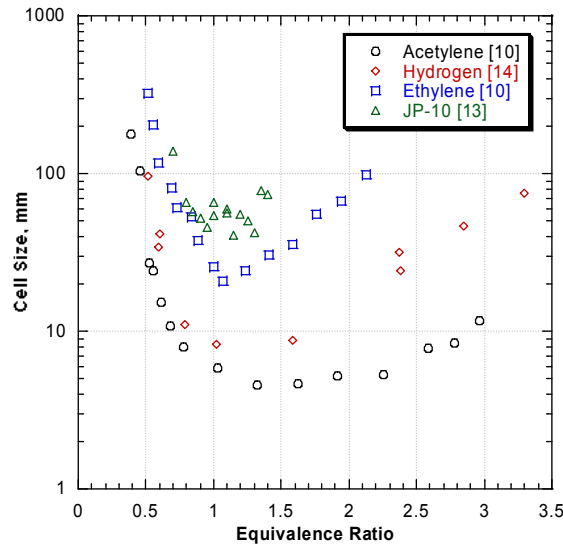
$$E_{crit} = 3.375 \lambda^3 \quad (2)$$

Although the two equations appear to be different, the important point is that the critical initiation energy varies with the cube of the detonation cell size, which means that a decrease in cell size is an indication of improved detonability.

The detonation cell size is a physical characteristic of a detonation wave as it propagates, as shown in Fig 1. A more detailed discussion of detonation cell structure can be found in Fickett and Davis.<sup>12</sup> Figure 2 is a plot of detonation cell size as a function of equivalence ratio for acetylene, hydrogen, ethylene, and JP-10. JP-10 is a higher density liquid hydrocarbon with a density on the same order as that of JP-8. Acetylene, hydrogen, and ethylene are shown to have a smaller detonation cell size than JP-10 at corresponding equivalence ratios; therefore, it is inferred from Eqs. (1) and (2) that acetylene, hydrogen, and ethylene are more detonable than high-density liquid hydrocarbons. The data from Fig. 2 were compiled by Kaneshige and Shepherd<sup>5</sup> but experimentally determined elsewhere.<sup>10,13,14</sup>



**Figure 1. Representative two-dimensional detonation cell structure**



**Figure 2. Plot of detonation cell size as function of equivalence ratio for four fuels in air.**

If a liquid hydrocarbon fuel is heated to a sufficiently high temperature ( $\sim 800$  K), it will begin to undergo endothermic reactions known as thermal cracking.<sup>15</sup> As a result of these endothermic reactions, the complex hydrocarbon bonds begin to break apart and form smaller, lighter hydrocarbons and hydrogen.<sup>16,17</sup> Huang et al.<sup>15</sup> have shown with Gas Chromatograph/Mass Spectrometer (GC/MS) analysis that when JP-8 was heated to  $\sim 960$  K, a substantial shift in composition occurred. The concentrations of heavy liquid hydrocarbons (decane, undecane, dodecane, tridecane, tetradecane, and pentadecane) decreased, whereas that of lighter liquid hydrocarbons (butene, benzene, and toluene) increased.<sup>15</sup> As these lighter hydrocarbons are formed (and heavier hydrocarbon concentration decreases) the ignition and DDT times are likely reduced. Using a gas chromatograph, Huang et al.<sup>15</sup> showed that endothermic reactions also produced hydrogen and several gaseous hydrocarbons, such as ethylene. As shown in Fig. 2, hydrogen and ethylene have smaller cell sizes, leading to increased detonability. Austin and Shepherd<sup>13</sup> have shown that adding hydrogen or ethylene to a liquid hydrocarbon decreases the cell size of the mixture, thereby increasing detonability.

Zeolite catalytic coatings have been used in several experiments<sup>15-19</sup> to aid in fuel cracking and minimize coking. Huang et al.<sup>19</sup> found that a wall-supported zeolite catalyst would permit an experiment to run five times longer. Galligan<sup>18</sup> found that a zeolite catalyst could be used to obtain  $>90\%$  conversion of JP-10 to other hydrocarbons. Shepherd et al.<sup>16</sup> showed that the use of a zeolite catalyst could increase the percent of JP-10 conversion by an order of magnitude over that of thermal cracking alone.

### III. Experimental Setup and Instrumentation

#### A. Facilities and PDE Details

This research was conducted in the Pulsed Detonation Research Facility (PDRF), which is located at Wright-Patterson AFB in Ohio. This facility was described in detail elsewhere,<sup>20</sup> and only the details that are relevant to the current research are provided here. The PDE for this study consisted of the valve train from a GM quad-four-engine head with two 1.83-m-long, Schedule-40 stainless-steel detonation tubes (50.8-mm diameter); each tube had a 1.22-m-long Schelkin-like spiral, with one end adjacent to the closed end of the detonation tube, to promote DDT.<sup>21</sup> Each detonation tube had an inconel heat exchanger (described later).

The PDE cycle consisted of three equally timed phases--fill, fire, and purge, as shown in Fig. 3. During the fill phase, the intake valves were opened to fill the PDE detonation tube with a volume of premixed fuel and air that was equal to the volume of the detonation tube (fill fraction of one). For all tests the fill air was initially heated to 394 K prior to mixing with the fuel. During the fire phase, spark energy was released, causing the formation of a deflagration wave that transitioned to a detonation wave. The ignition system provided spark pulses through modified spark plugs, with each spark plug supplying an ignition energy of 115 mJ. The spark delay after the intake valves were closed was 6 ms. During the purge phase, the exhaust valves were opened to fill the detonation tube with a volume of air (unheated) that was equal to one-half the volume of the detonation tube (purge fraction of 0.5). The purge air cooled the detonation tube and removed a portion of the exhaust gases, preventing auto-ignition. The PDE firing frequency was kept constant at 15 Hz for all testing.

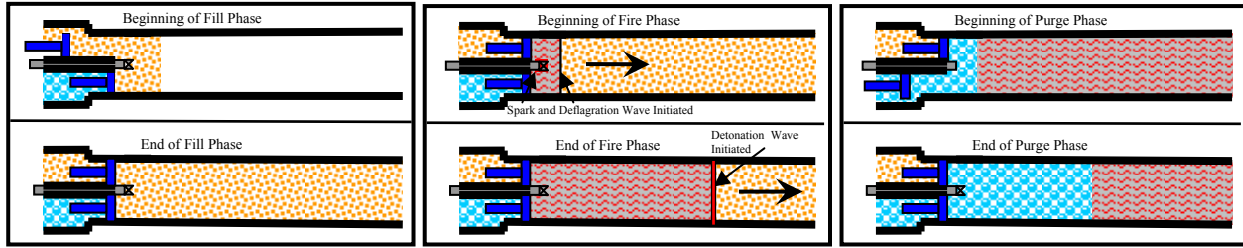


Figure 3. Diagrams of fill, fire, and purge phases of PDE cycle.

#### B. Fuel Heating System

The liquid fuel required for this testing was supplied by two hydraulic bladder accumulators that were pressurized by nitrogen. The nitrogen pressurized the fuel above the critical pressure for the duration of the test to prevent phase change. The fuel was pressure fed to the inlet of the fuel heating system (FHS). The FHS consisted of two inconel heat exchangers, a fuel filter assembly, fuel injection nozzles, instrumentation, and associated tubing and fittings necessary to connect the critical components. The flow path and instrumentation are shown in schematic and photographic form in Figs. 4(a) and 4(b), respectively. The fuel entered the test stand through a pneumatically-operated ball valve and then flowed through the heat-exchanger on tube three. The fuel was then routed through the heat-exchanger on tube two and through the filter to the fill-air manifold, where it was injected into the air stream via the fuel-injection nozzles. The fuel filter was used to remove the coking that was formed as a result of thermal cracking of the fuel.<sup>22</sup> The fuel lines that carried heated fuel (fuel that had traversed through a heat-exchanger) were insulated with a ceramic-tape insulation to prevent heat loss [Note: Insulation is removed in Fig. 4(b) for visual clarity].

The fuel mass flow rate of the nozzles is proportional to the square root of the pressure drop across the fuel nozzles and the fuel density.<sup>23,24</sup> To compensate for the decrease in fuel density during heating of the fuel in the supercritical regime, the charge pressure of the accumulators was increased to maintain a constant fuel mass flow rate. The accumulator charge pressure was varied during the test using a pneumatic dome-loaded regulator [for details, see Ref. 25].

To minimize oxidative carbon deposition in the FHS, the JP-8 was de-oxygenated through a nitrogen sparging process, reducing the oxygen concentration to <1 ppm. The sparging process involved bubbling a volume of nitrogen through the JP-8 to displace the dissolved oxygen in the fuel. The volume of nitrogen necessary to reduce the oxygen concentration to acceptable levels was determined experimentally in previous work;<sup>26</sup> and to ensure acceptable levels, a factor of safety of two was applied to all nitrogen volume calculations.

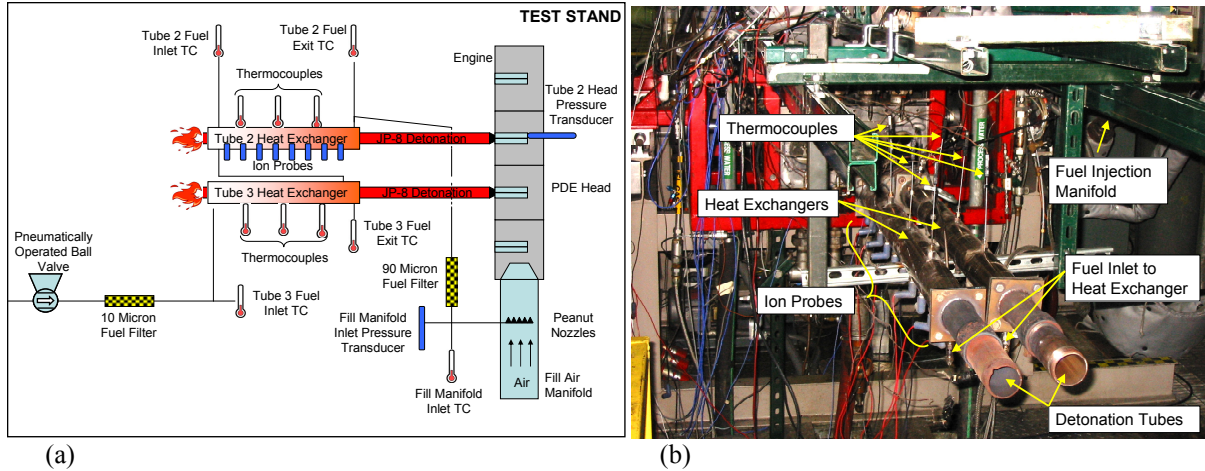


Figure 4. (a) Diagram and (b) photograph of the PDE with the fuel heating system and instrumentation.

### C. Heat Exchangers

Two identical concentric-tube heat exchangers were fabricated for this research. Each 0.91-m-long heat exchanger was fabricated with a 50.8-mm-dia, inconel-625, Schedule-10 inner tube and a 63.5-mm-dia, inconel-600, Schedule-40 outer tube allowing a 1.22 mm annular gap. A photograph of one of the heat exchangers, with the associated instrumentation ports, is shown in Fig. 5.

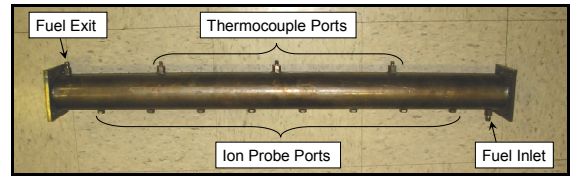


Figure 5. Photograph of heat exchanger.

### D. Zeolite Catalytic Coating

The inner walls of the two heat exchangers and the tubing between them and the fuel injection nozzles were coated with an inexpensive zeolite catalyst in a ceramic-like binder. The catalyst was applied by a contractor using a proprietary method. The zeolite structure is known to be composed of a silica-alumina, but the catalytic agent is proprietary information. As mentioned earlier, the catalyst was applied to decrease coke deposition and increase fuel cracking.

### E. Instrumentation

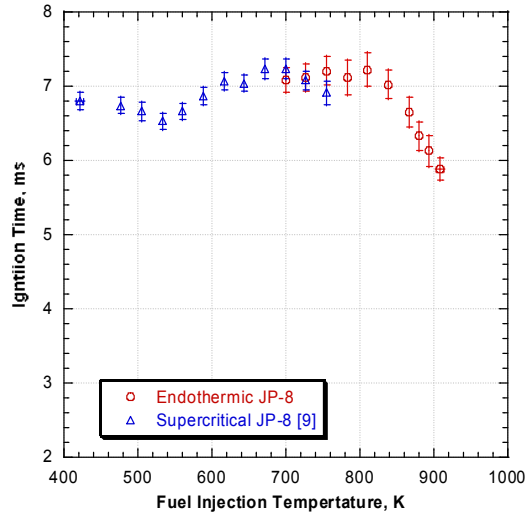
Ion probes were placed in ports, spaced 0.102 m apart, along the length of the detonation tube and heat exchanger (see Figs. 4 and 5), and were used to measure the velocity of the combustion wave (wavespeed). Combustion waves propagating at speeds within 10% of the upper Chapman-Jouguet point (assumed to be 1800 m/s) were considered to be detonation waves. Thermocouples were placed in the center of the flow path to gather temperature data at the inlet and outlet of each heat exchanger (J-type) and at the inlet to the fill-air manifold (T-type). Additional J-type thermocouples were placed in the thermocouple ports (see Fig. 5) in both heat exchangers to determine fuel temperature within the heat exchanger. External heat-exchanger wall temperatures were measured with J-type thermocouples that were mounted externally by compression clamps on the PDE detonation tube. A pressure transducer was situated at the closed end of the detonation tubes to measure the pressure that was used to determine the ignition time.

## IV. Results and Discussion

The experimentally determined ignition time, DDT time, and DDT distance are plotted as a function of fuel-injection temperature (Figs. 6, 7, and 8, respectively) and equivalence ratio (Figs. 9, 10, and 11, respectively). Additionally, the results of a thorough examination of the coke deposition and catalyst condition are presented. Each data point represents the mean value of 30 - 40 ignitions. The total experimental uncertainty is presented whenever possible. Results presented as a function of equivalence ratio are shown with flash-vaporized JP-8 data determined by Helfrich et al.<sup>27</sup> Results presented as a function of fuel injection-temperature are shown with the supercritical fuel-injection results for JP-8 that were determined by Helfrich et al.<sup>9</sup> Results presented as a function of fuel injection temperature were collected with a near-stoichiometric mixture of fuel and air. The measured equivalence ratio was found to vary no more than 2%.<sup>11</sup>

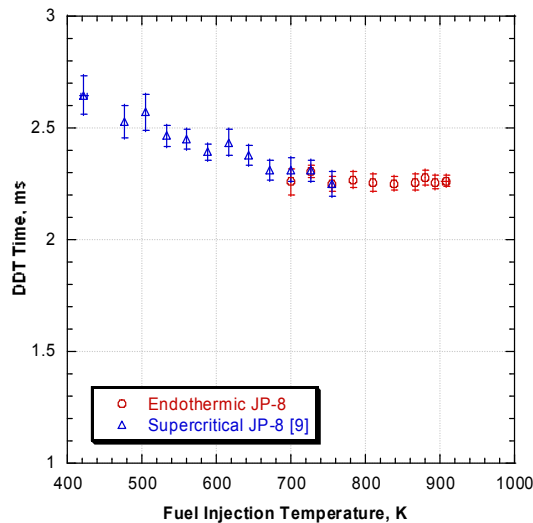
### A. Results as a Function of Fuel-Injection Temperature

Figure 6 is a plot of ignition time as a function of fuel-injection temperature for a near-stoichiometric JP-8/air mixture. The ignition time decreases rapidly at temperatures above 800 K, which is the threshold for significant cracking to occur.<sup>15</sup> The ignition time is reduced by 19% when the fuel is heated from 800 K to 900 K. This appealing trend implies that further elevation of the fuel temperature will result in reductions in ignition time, although the temperature limit to the trend is unknown. The endothermic data matches well with the supercritical data of Helfrich et al.<sup>9</sup> in the overlapping range.



**Figure 6. Plot of ignition time as function of fuel-injection temperature for JP-8/air mixture.**

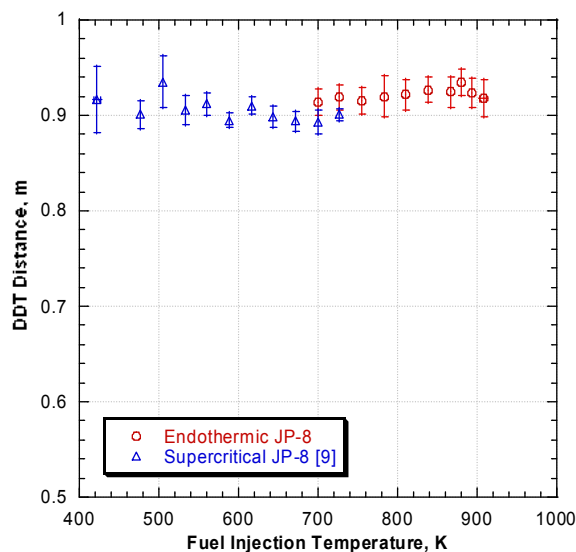
Figure 7 is a plot of DDT time as a function of fuel-injection temperature for a near-stoichiometric JP-8/air mixture. The DDT time appears to be independent of fuel-injection temperature, once the fuel has begun to crack, with a constant DDT time of 2.25 ms. The data of Helfrich et al.<sup>9</sup> showed a nearly linear decrease in DDT time that does not appear in the present research, although the values of DDT time match quite well in the overlapping temperature range. The detonations become more consistent with increasing fuel-injection temperature, as shown by the decrease in uncertainty with increasing fuel-injection temperature.



**Figure 7. Plot of DDT time as function of fuel-injection temperature for JP-8/air mixture.**



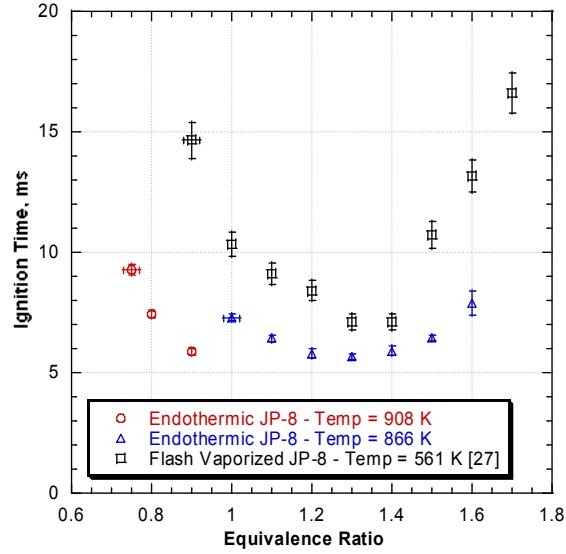
The DDT distance plotted as a function of fuel-injection temperature for a near-stoichiometric JP-8/air mixture is shown in Fig. 8. The DDT distance is independent of fuel-injection temperature, which is consistent with the data of Helfrich et al.<sup>9</sup> However, the magnitude of the DDT distance was found to be slightly higher than in the data of Helfrich et al.<sup>9</sup> because the earlier experiments incorporated a 0.914-m spiral and the current experiment was performed with a 1.22-m spiral. The longer spiral creates drag on the combustion wave, likely delaying detonation transition slightly.



**Figure 8. Plot of DDT distance as function of fuel-injection temperature for JP-8/air mixture.**

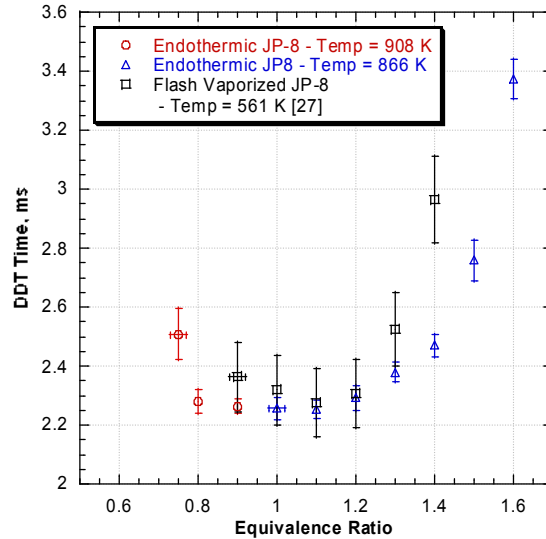
## B. Results as a Function of Equivalence Ratio

Figure 9 is a plot of ignition time as a function of equivalence ratio for a JP-8/air mixture at three temperatures. Because of fuel-system limitations, temperatures in excess of 866 K could not be reached for equivalence ratios greater than stoichiometric. As expected, a significant decrease in ignition time at all equivalence ratios is observed in JP-8 data at 866K, as compared to JP-8 data at 561K. For most equivalence ratios, at least a 30% reduction in ignition time occurs. The JP-8 data at 908 K show a further reduction in ignition time, with a 60% reduction at an equivalence ratio of 0.9. The JP-8 results at 866 K and 908 K are more consistent than those at 561 K, as demonstrated by a reduction in uncertainty. Additionally, the lean ignition limit of the JP-8 at 908 K is 0.75, which is significantly better than the 0.9 lean limit at 561 K.



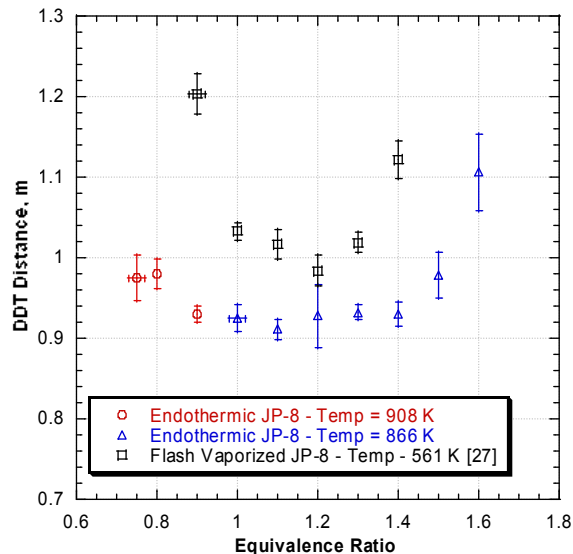
**Figure 9. Plot of ignition time as function of equivalence ratio for JP-8/air mixture.**

A plot of the DDT time as a function of equivalence ratio for a JP-8/air mixture at three temperatures is shown in Fig. 10. The minimum DDT time, occurring at an equivalence ratio of 1.1 for both the endothermic and flash-vaporized JP-8, is not affected by the fuel cracking. However, at equivalence ratios  $>1.2$  and  $<1.0$ , the endothermic JP-8 produces a shorter DDT time. The detonations occur more consistently with the endothermic JP-8 than the flash-vaporized JP-8, as shown by the smaller uncertainty. In addition, both the rich and lean detonability limits have been expanded. To the authors' knowledge, the lean limit of 0.75 is the leanest JP-8/air mixture to be detonated through spark initiation and DDT using a spiral in a PDE.



**Figure 10. Plot of DDT time as function of equivalence ratio for JP-8/air mixture.**

Figure 11 is a plot of DDT distance as a function of equivalence ratio for a JP-8/air mixture at three temperatures. The DDT distance of the endothermic JP-8 is shorter (greater than 10 cm for most equivalence ratios) than that required for the flash-vaporized JP-8 for all equivalence ratios. Both the flash-vaporized JP-8 experiment performed by Helfrich et al.<sup>27</sup> and the present experiment used a 1.22-m-long spiral, facilitating a good comparison of DDT distance.

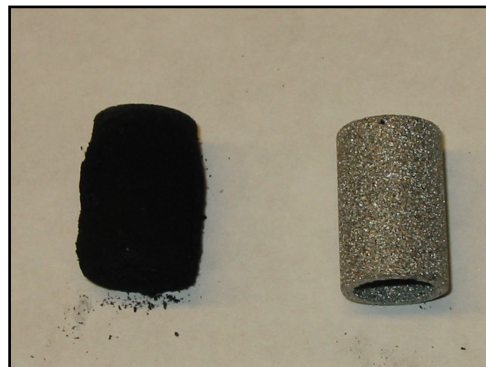


**Figure 11. Plot of DDT time as function of equivalence ratio for JP-8/air mixture.**

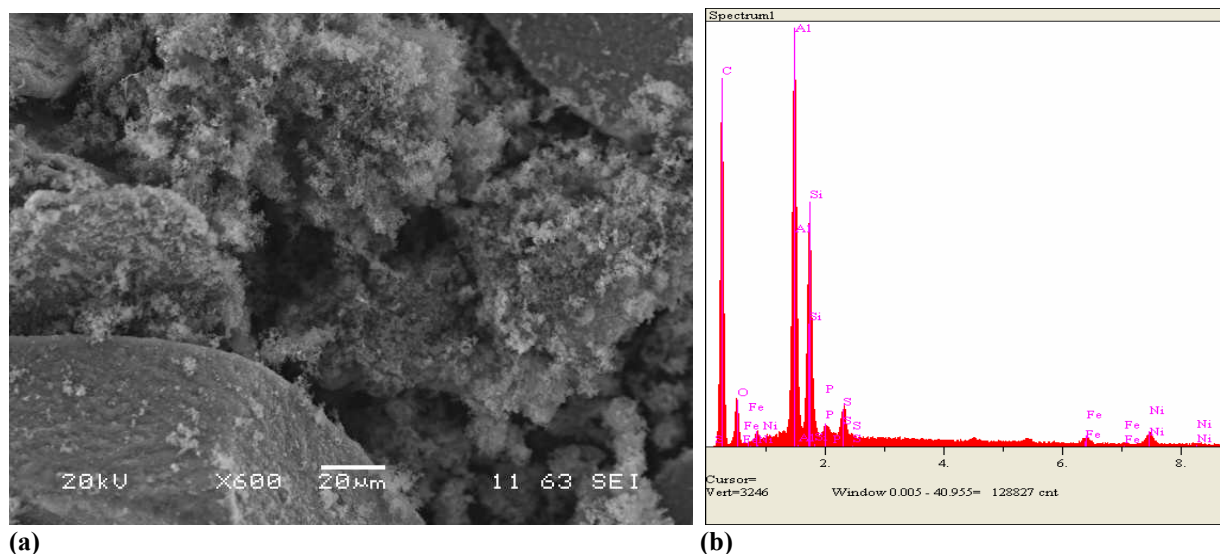
### C. Analysis of Coke Deposit

After approximately 5 hr of accumulated run time, a significant increase in pressure drop across the fuel filter (see Fig. 4) was observed. The filter was subsequently removed and cleaned. An inspection of the filter housing resulted in the identification of a large quantity of loose black deposits, suspected to be coke. Additionally, the filter element was clogged with the same black deposits. Figure 12 is a photograph of the clogged filter element adjacent to a new one.

To confirm the content of the deposit, a sample was analyzed in a scanning electron microscope (SEM) that is equipped with an energy-dispersive x-ray detector (EDX). The SEM is capable of capturing photographs of a sample at the micron level (micrographs). The EDX is capable of identifying the elemental components of a sample, although it is not quantitatively accurate for determining the concentrations of carbon and oxygen. Figure 13(a) is a SEM micrograph of the carbon sample at 600x magnification. The large smooth structure in the lower-left corner of Fig. 13(a) is probably a carbon structure. Figure 13(b) is a plot of the relative concentrations of the elemental species as measured by the EDX. While the exact concentration of carbon cannot be determined with the EDX, it is apparent that significant carbon is present. In addition to carbon, two other elements are prominent, aluminum and silicon. The EDX data indicate that, excluding carbon and oxygen, 42.4% of the sample is aluminum and 41.5% of the sample is silicon. As mentioned earlier, the zeolite structure is made of silica-alumina. Thus, it is concluded that some of the zeolite catalyst has flaked off during testing, although no degradation in PDE performance was observed. The extremely porous structures apparent throughout Fig. 13(a) are probably the zeolite fragments.

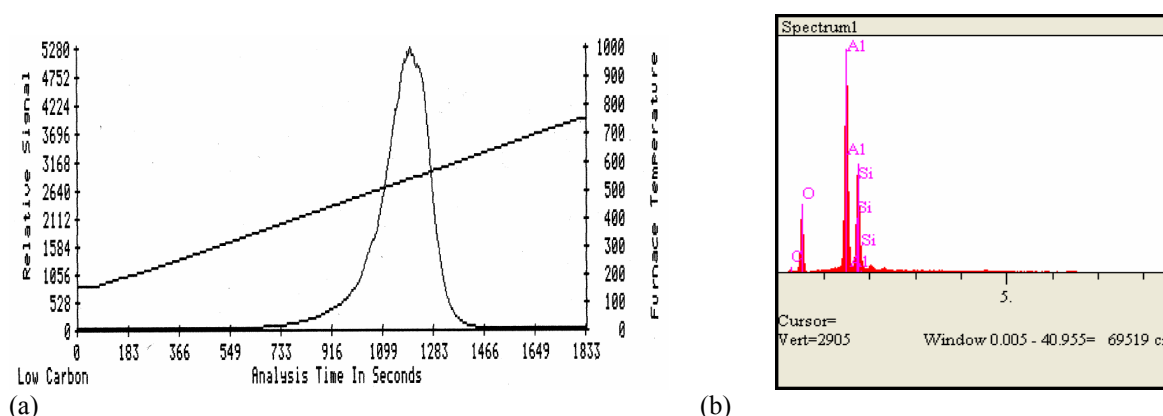


**Figure 12. Photograph of coke-filled filter element (left) and new filter element (right).**



**Figure 13. (a) SEM micrograph of black powder from filter housing, magnified to 600x, and (b) plot from EDX of relative concentrations of elements found in black deposit.**

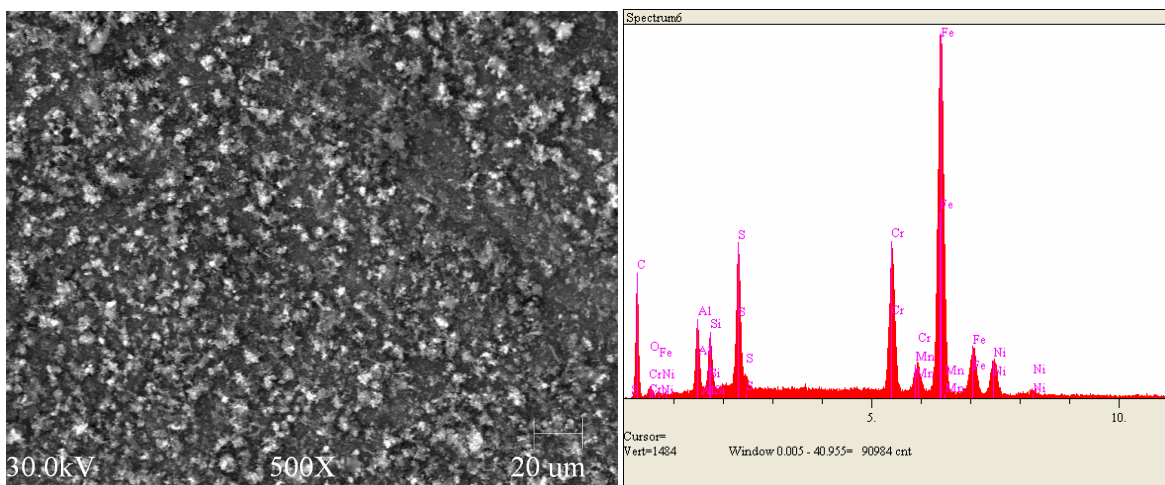
To determine the concentration of carbon, the sample was further analyzed using a Leco RC 412 surface carbon determinator (SCD). The SCD operates by heating the sample in a furnace with  $O_2$ , thereby oxidizing the carbon in the sample to  $CO_2$ .<sup>28</sup> The  $CO_2$  is then measured using a calibrated IR detector to determine the concentration of carbon in the sample.<sup>28</sup> The SCD was set to heat the sample, starting at  $150^\circ C$ , increasing  $20^\circ C/min$ , ending at  $750^\circ C$ , and holding the sample at  $750^\circ C$  for another 10 min. Figure 14(a) is a plot of the relative signal (amount of  $CO_2$ ) and temperature (shown in  $^\circ C$  on plot) as a function of time. The majority of the sample is oxidized between 650 K and 750 K, which is indicative of carbon rings. The SCD measurement showed that the sample contained 38% carbon. The portion of the sample that was left after the SCD test (49% by mass) is comprised of nonoxidizable elements, or ash. The ash was then analyzed with the SEM and the EDX. Figure 14(b) is a plot of relative concentrations of the ash. As expected, the only compounds remaining were aluminum and silicon. Therefore, approximately one-half of the deposit collected from the filter housing was composed of zeolite fragments.



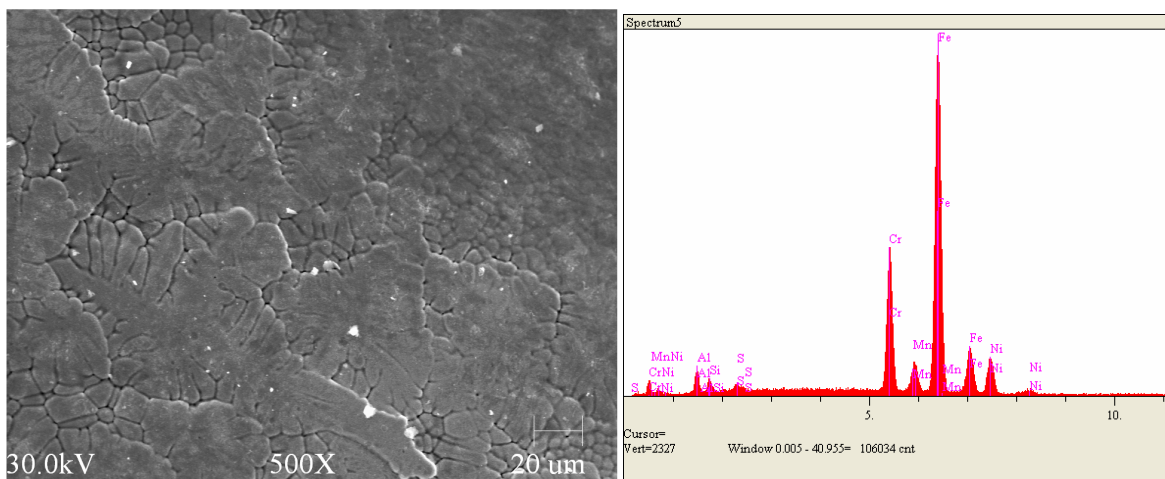
**Figure 14. (a) Plot from SCD of relative signal intensity (oxidation level) and furnace temperature (in  $^\circ C$ ) as function of time, and (b) plot from EDX of relative concentrations of nonoxidizable ash.**

Because of the large amount of coking and zeolite fragments found in the filter housing, it was suspected that the zeolite catalyst was clogged with coke, although no reduction in performance was noted. When the zeolite structure in a catalyst becomes clogged, the fuel molecules cannot move through structure, rendering it useless. To determine the state of the zeolite structure, a section of the tubing directly upstream of the fuel filter was removed, and the surface with the catalyst was examined with the SEM and the EDX. Figure 15(a) is an SEM micrograph of the catalyst after use (5 hr of operation), and Fig. 15(b) is a plot from the EDX of the relative concentration of the

elements detected in the used catalyst. Additionally, a section of tube with fresh catalyst was examined with the SEM and EDX for comparison purposes. Figure 16(a) is an SEM micrograph of the fresh catalyst, and Fig. 16(b) is a plot from the EDX of the relative concentration of the elements detected in the fresh catalyst. Comparing Figs. 15(a) and 16(a), a distinct difference in the surface texture is apparent. The fresh catalyst is very smooth, with small cracks resulting from the application process, whereas the used surface is covered with micron-sized structures. The small structures on the surface of the used catalyst are probably coke deposits. This hypothesis is supported by the comparison of Figs. 15(b) and 16(b). The fresh catalyst contains no trace of carbon, whereas the used catalyst contains a large concentration of carbon. Therefore, although no noticeable reduction in performance, it is concluded that the catalyst was covered in coke deposits after 5 hr of operation.



**Figure 15. (a) SEM micrograph of used catalyst (5 hr of operation), and (b) plot from the EDX of relative concentration of elements detected in used catalyst.**



**Figure 16. (a) SEM micrograph of fresh catalyst, and (b) plot from EDX of the relative concentration of elements detected in fresh catalyst.**

## V. Conclusions

This research marked the first analysis of the effect of thermal and catalytic cracking of JP-8 on key PDE performance parameters, including ignition time, DDT time, and DDT distance. Ignition time for a JP-8/air mixture was found to decrease rapidly when the fuel was heated above 800 K. DDT time and distance were found to be independent of temperature in the range tested at stoichiometric conditions, but the consistency of detonations increased. Endothermic JP-8 was found to require a shorter ignition time, DDT time, and DDT distance for the majority of equivalence ratios, as compared to flash-vaporized JP-8, with reductions in ignition time of up to 60%.

Furthermore, both the ignition and detonability limits were expanded by cracking the fuel, with lean limits at an equivalence ratio of 0.75.

Analysis of coke deposition resulting from thermal cracking of the JP-8 showed a large concentration of carbon molecules, probably large carbon rings. In addition to the carbon, a substantial quantity of silicon and aluminum was present in the filter, suggesting that the zeolite structure had deteriorated. The catalyst was also found to be completely covered by coke deposits after 5 hr of operation, although no degradation in performance was observed.

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